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Three-Dimensional Motions in the Vicinity of Merging Polar Front and Subtropical Jet Streams

Beaulieu, Eugene Leo

Monterey, California. Naval Postgraduate School

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UNITED STATES
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THESIS

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by

Eugene Leo Beaulieu
Lieutenant, United States Navy
B.S., University of Washington, 1961

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ABSTRACT

A developing surface frontal system with an overlying polar front jet and subtropical jet stream merging region was present over the continental United States during 22 to 24 March, 1966. Possible cross-over flow between these two jet streams has been studied in detail by isentropic air trajectories at four potential temperature levels from 310 K to 335 K.

The results of the trajectory analyses on the four θ surfaces have indicated a cross-over of air parcels from the subtropical jet stream to the polar front jet stream. No evidence has been found for a reciprocal relationship for air parcels initially associated with the polar front jet between 310 K and 335 K isentropic levels.

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LIST OF SYMBOLS

SYMBOL	MEANING
c_p	specific heat at constant pressure
dd	wind direction
f	Coriolis parameter
ff	wind speed
g	acceleration of gravity
M	Montgomery stream function $= c_p T + gZ$
$M_{2\text{-comp}}$	final computed M value
$M_{2\text{-obs}}$	final observed M value
ΔM	local change of M
P	potential vorticity $= -\eta_\theta \left(\frac{\partial \theta}{\partial P}\right)$
η_θ	absolute vorticity of air parcel on constant θ surface $= f + V_\theta / R_s - \partial V_\theta / \partial n_\theta$
P_p	pressure at a standard or significant level
P_θ	pressure at a θ surface
R	gas constant
R_s	radius of curvature of streamline
t	time
T	temperature
$\bar{T}$	average T of layer between P_p and P_θ
T_θ	T at a θ surface
θ	potential temperature
u	x-component of horizontal wind
v	y-component of horizontal wind
V_θ	wind speed on a θ surface
$\bar{\omega}$	mean vertical motion in mb/12hrs

SYMBOL	MEANING
Z	geopotential height above mean sea level
Z_p	geopotential height of isobaric surface

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SECTION I

INTRODUCTION

Studies by Reiter and Whitney (1965) of the region where a polar front jet and a subtropical jet stream are in close proximity to each other have produced a provocative hypothesis that there exists a cross-over flow between the two respective jets. One corollary is that certain air parcels in the polar front jet, rather than follow a normal cyclonic trajectory over the continental United States, cross-over and proceed along a trajectory path similar to that of air parcels in the subtropical jet stream. A second corollary proposes that, rather than follow a basically anticyclonic trajectory, certain air parcels in the subtropical jet cross-over and then continue along a trajectory path similar to that of air parcels in the polar front jet stream flow.

Regardless of the validity of the hypothesis, the isentropic trajectory of a representative air parcel in either jet can be computed by the method developed by Danielsen (1961). This computational method describes with considerable accuracy the movement of air parcels along an isentropic surface. However, unlike several other approaches to calculating air trajectories which assume that air parcels move quasi-horizontally on a surface of constant height or pressure, the Danielsen approach gives the necessary third dimension — a measurement of the average vertical motion.

Throughout this study diabatic effects on trajectory motion in this non-precipating region are neglected because diabatic contributions to vertical motion are normally small compared to adiabatic contributions.

During late March 1966 a strong developing surface low with associated frontal systems moved east-northeast across the continental United States. Also associated with this surface system were a strong polar front and a subtropical jet stream in close proximity to each other as illustrated in Figure 1. The period between 22 March 0000 GMT to 24 March 0000 GMT was selected as being most favorable for testing the hypothesis of Reiter and Whitney (1965).

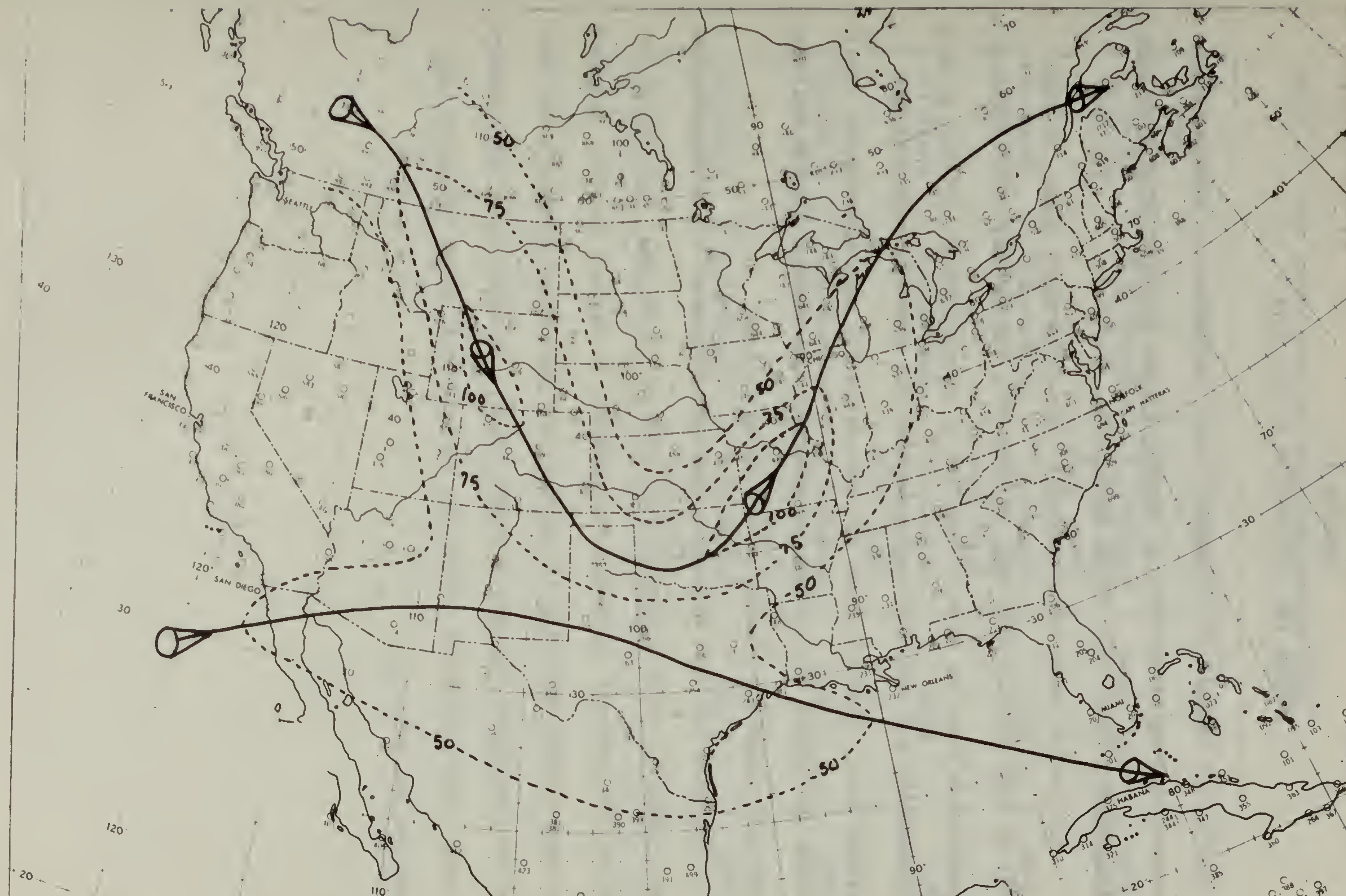


Fig. 1. 23 March 1966, 1200 GMT subtropical and polar front jet stream analysis on the 300 mb isobaric surface. Dashed lines are isotachs (units kts).

SECTION II

NATURE AND ACQUISITION OF THE DATA

All the data in the analysis comes from radiosonde and rawinsonde checked data found in the U.S. Weather Bureau Northern Hemisphere Data Tabulations for 22, 23, and 24 March 1966.

The period under study contains five observation times, 22 0000 GMT, 22 1200 GMT, 23 0000 GMT, 23 1200 GMT, and 24 0000 GMT. For each observation time, an area of interest is determined by plotting an area encompassing not only the surface system but also the region ot the merging jets. Table 1 shows the data areas for each observation time. Having delineated the regions of interest, the checked data is utilized from each upper-air station within these regions.

The data for each upper-air station consists of all standard pressure levels in 50 mb intervals from 1000 mb to 200 mb. From 200 mb to 100 mb the interval is 25 mb. Temperature in degrees Celsius, heights in meters, wind direction in degrees, and wind speed in meters per second are tabulated for each standard level. In addition to the standard levels, the significant levels are recorded with their tabulated temperatures and heights

Table 1. Data areas used for each observation time.

OBSERVATION TIME	NORTH	SOUTH	WEST	EAST
22 March 0000 GMT	U.S.-Canada Border	U.S.-Mexico Border and Gulf Coast	West Coast U.S.	90°W
22 March 1200 GMT	U.S.-Canada Border	U.S.-Mexico Border and Gulf Coast	115°W	80°W
23 March 0000 GMT	U.S.-Canada Border	U.S.-Mexico Border and Gulf Coast	105°W	75°W
23 March 1200 GMT	U.S.-Canada Border	U.S.-Mexico Border and Gulf Coast	105°W	75°W
24 March 0000 GMT	U.S.-Canada Border	U.S.-Mexico Border and Gulf Coast	105°W	65°W

SECTION III

THE MONTGOMERY STREAM FUNCTION COMPUTER PROGRAM

Assuming $d\theta/dt = 0$, the equations of motion in θ coordinates become

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x_\theta} + v\frac{\partial u}{\partial y_\theta} = -\frac{\partial M}{\partial x_\theta} + fv \tag{1}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x_\theta} + v\frac{\partial v}{\partial y_\theta} = -\frac{\partial M}{\partial y_\theta} - fu\,, \tag{2}$$

where the isentropic stream function is defined as

$$M = c_p T + gZ\,. \tag{3}$$

For the air trajectory method as derived by Danielsen (1961) and later outlined by Mahlman (1965), the Montgomery stream function is given by

$$M = c_p T_\theta + g Z_p + R\overline{T}(\ln P_p - \ln P_\theta)\,. \tag{4}$$

As observed by Danielsen (1959), large errors of M result if values of T_θ and P_θ are selected independently of each other from the plotted soundings. Consequently, for this program, the dependent relationship of T_θ and P_θ on an isentropic surface, as given in Poisson's equation, allows M to be written

$$M = c_p T_\theta + g Z_p + R\overline{T}\ln\left[\frac{P_p}{1000}\left(\frac{\theta}{T_\theta}\right)^{c_p/R}\right], \tag{5}$$

as shown in Mahlman and Kamm (1965). M is now in a convenient computational form which can be handled readily by the computer.

The basic program is presented in Appendix I and will be briefly

outlined in this section. After reading in the data, all temperatures are converted to degrees Kelvin. Potential temperatures are next computed for each level. For this study, a range of potential temperatures between 290 K and 350 K at 5° intervals is assigned for computation.

The data ~~is~~ are now searched for the first θ level above and below the predetermined θ level. With these two θ values and the predetermined θ value, T_θ is computed. P_θ is then computed from Poisson's equation using T_θ and θ. Finding next the first standard levels above and below the arbitrary isentropic surface and calculating $\bar{T}$ by summing the weighted mean temperatures between all data points from the lower standard level to the arbitrary θ level, the Montgomery stream function is computed in three segments according to equation (5). Finally, the wind direction and wind speed ~~is~~ are interpolated according to the procedure used by Mahlman and Kamm (1965). After completing the calculations for one particular isentropic surface at all stations in the data area, the procedure is repeated for the next higher relevant θ level.

The final computer output gives for each isentropic surface the M value, pressure, static stability, wind direction, and wind speed for all reporting stations. With these five parameters, the isentropic trajectories can be computed and checked for accuracy, thus enabling the three-dimensional tracking of selected air parcels.

SECTION IV

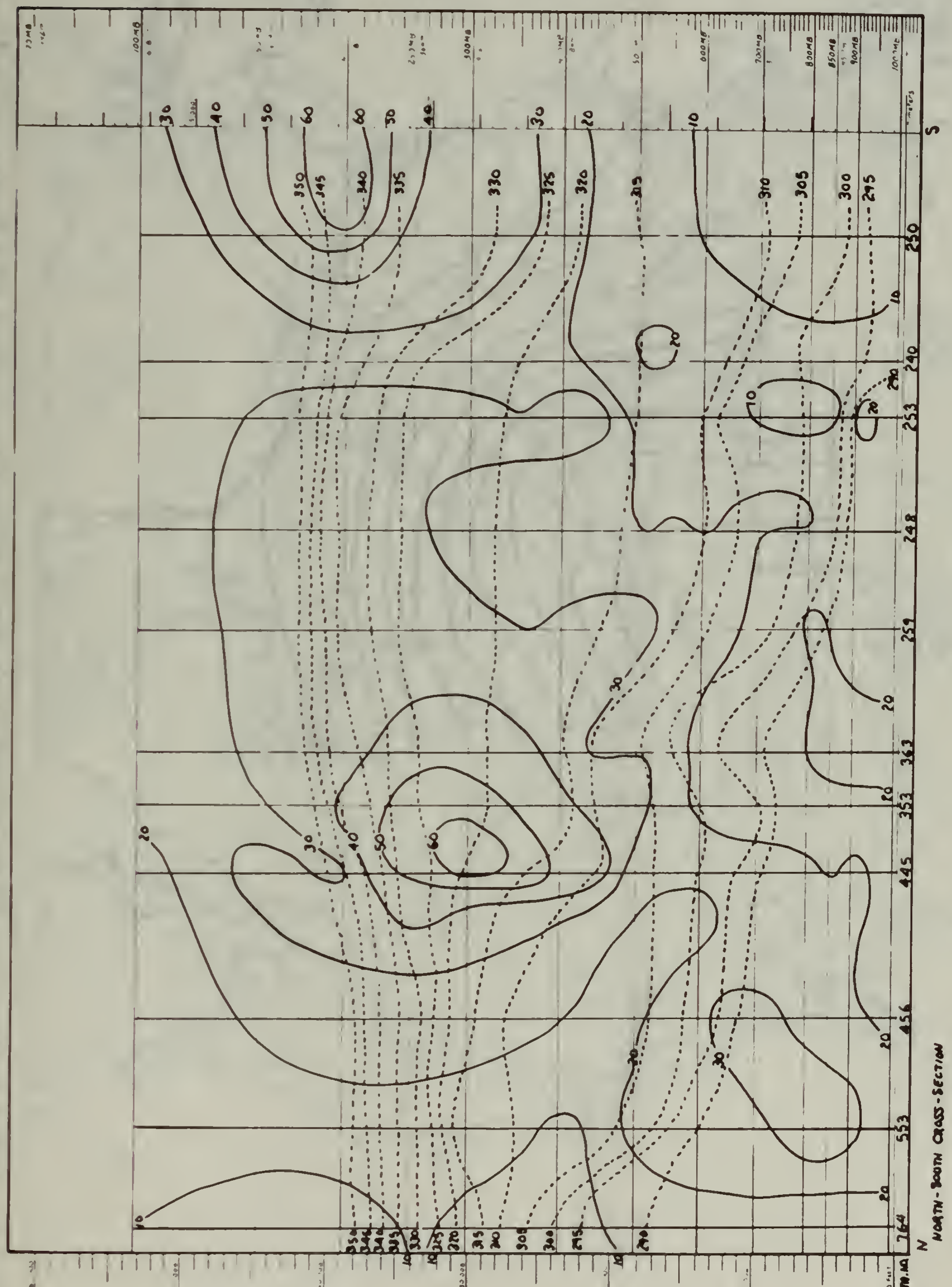
DETERMINATION OF RELEVANT ISENTROPIC SURFACES

Possessing now the computed parameters M, P_{θ}, wind direction and wind speed for all the isentropic surfaces at 5° intervals between 290 K and 350 K, the next step in the procedure is to determine particular θ levels which are representative of the isentropic surfaces present in the polar front jet and the subtropical jet streams.

The observation time 23 March 12000 GMT is selected as the synoptic map most representative of the five observation times. A north-south cross section on longitude 95° W is constructed with plotted values of wind speed and potential temperature as depicted in Figure 2. Analysis of this cross section shows that four isentropic surfaces might possibly be of interest — 310 K, 320 K, 330 K, and 335 K. These four θ surfaces are chosen because of their physical location with respect to both jet streams and their heights above sea level, so that there will be a minimum of orographic and lower level interference.

Basic maps are plotted on 1:15,000,000 scale charts for the four θ surfaces. Each of these isentropic surfaces is analysed for the Montgomery stream function using a 0.5×10^{7} cm^{2} sec^{-2} interval, for pressure using a 50 mb interval, and for wind speed using a 10 m sec^{-1} isotach interval. Figures 3, 4, and 5 are typical examples of these analyses.

Fig. 2. 23 March 1966, 1200 GMT north-south cross-section on longitude 95°W. Solid lines are isotachs (units m sec^{-1}); dashed lines are potential temperature (°K). 310 K, 320 K, 330 K, and 335 K are the isentropic surfaces chosen for trajectory analysis in this study.



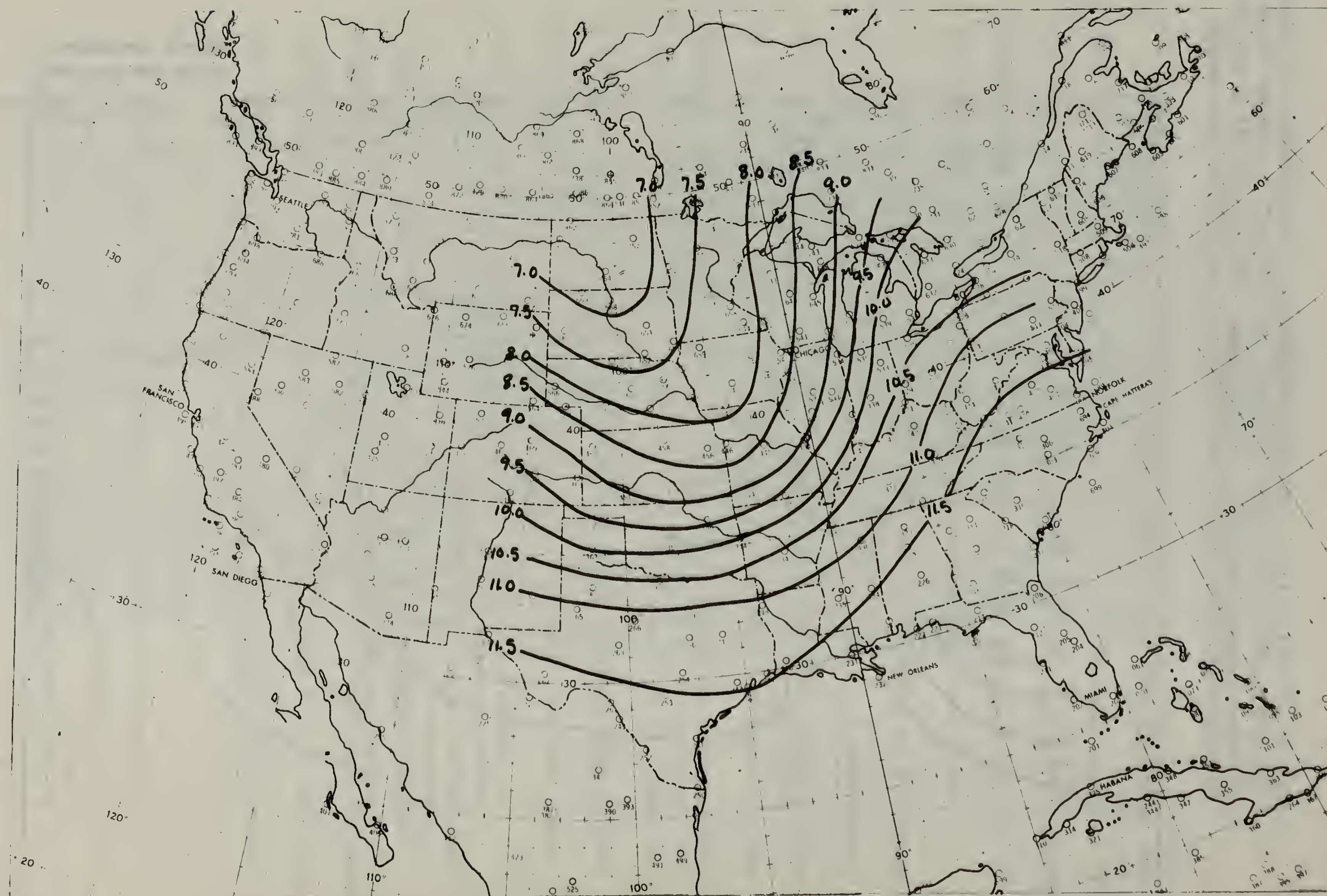


Fig. 3. 310K M analysis for 23 March 1966, 1200 GMT. To read true values of M (units 10^7 cm^2 sec^{-2}) add 300 to the labeled isolines.

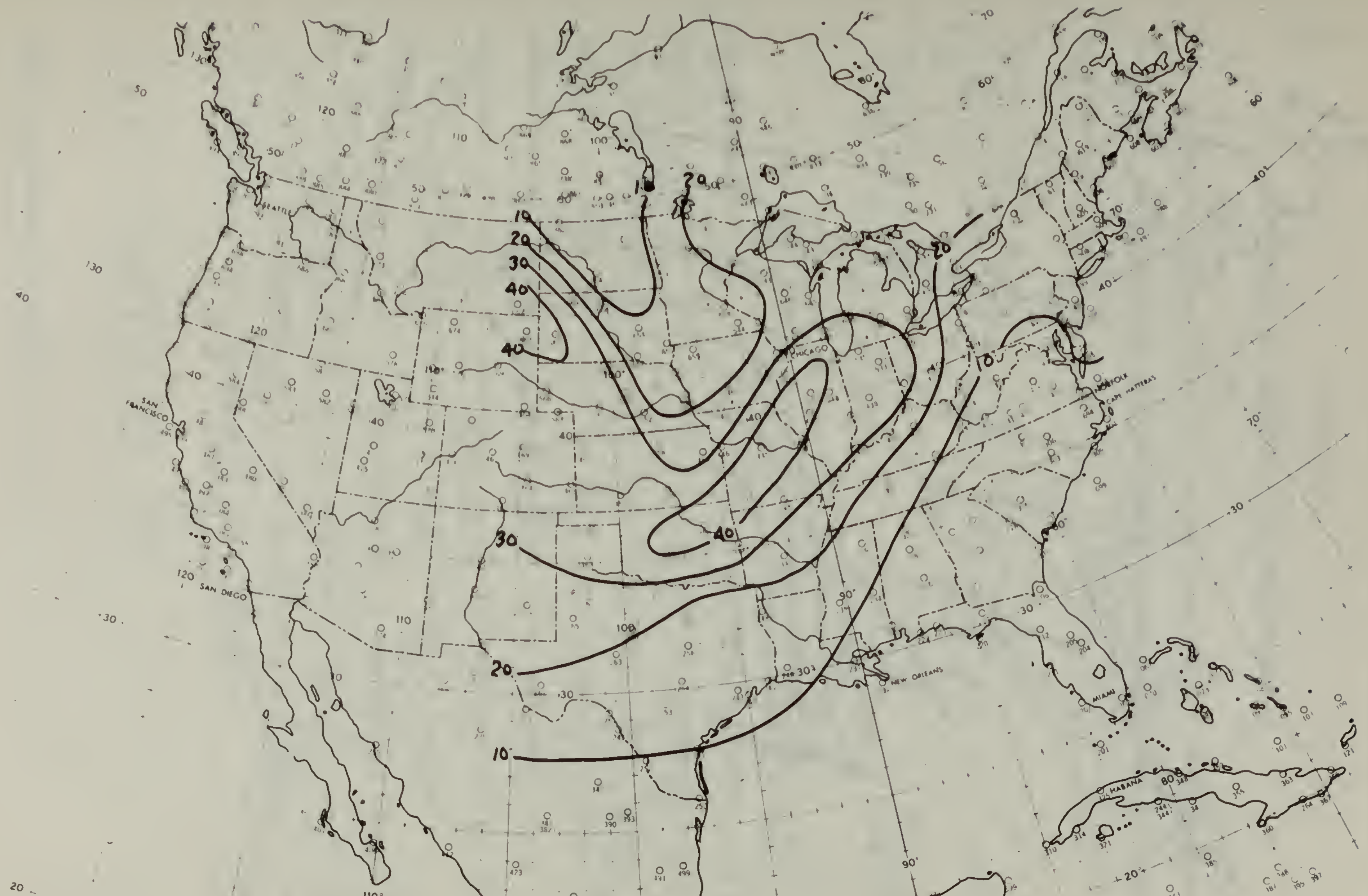


Fig. 4. 310 K isotach analysis for 23 March 1966, 1200 GMT. Wind speed expressed in m sec^{-1}.

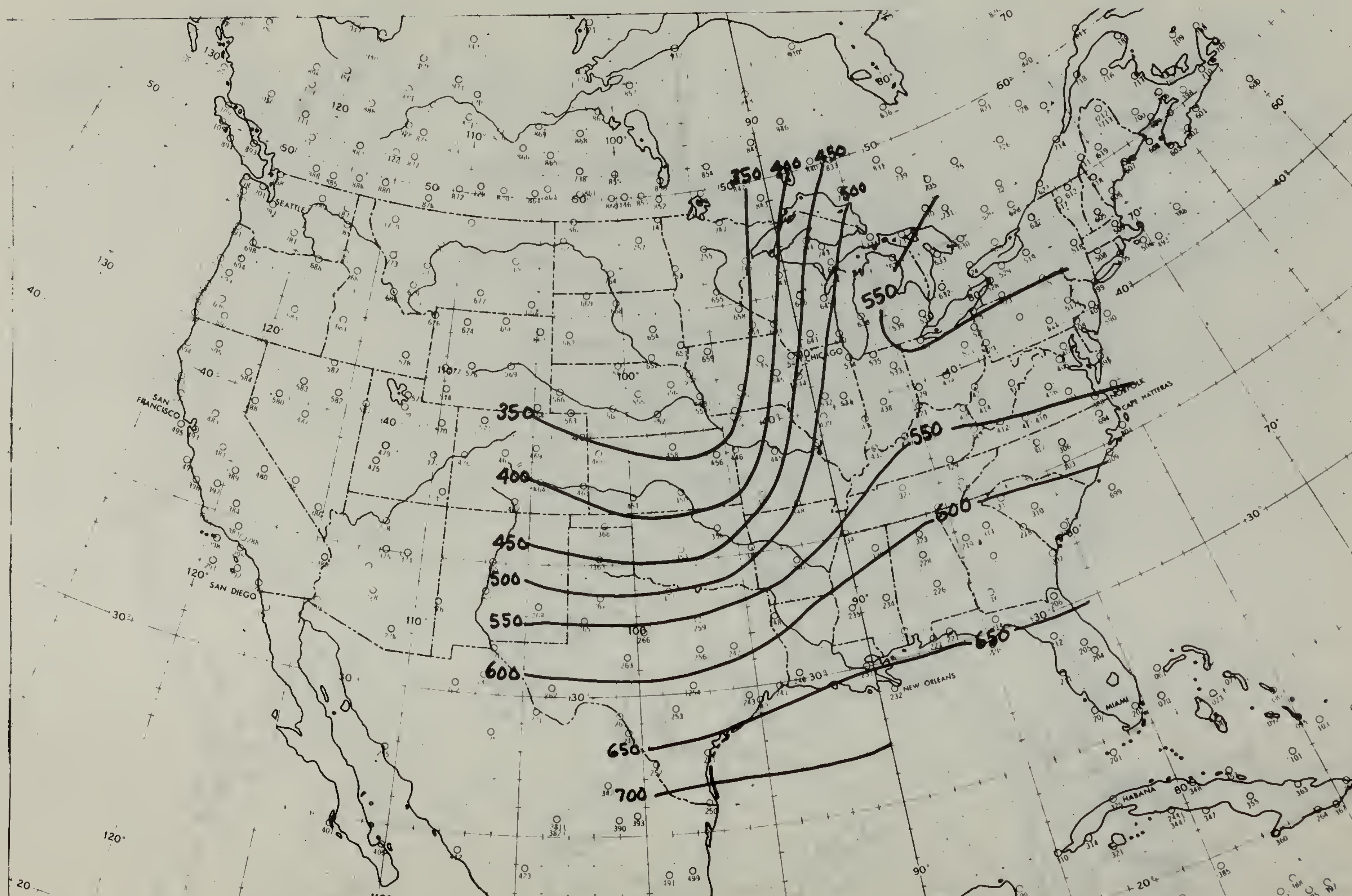


Fig. 5. 310 K pressure analysis for 23 March 1966, 1200 GMT. Pressure expressed in mb.

SECTION V

COMPUTATION OF ISENTROPIC AIR TRAJECTORIES

Mahlman's outline (1965) of the Danielsen method (1961) develops in detail the two working equations for computation of isentropic air trajectories,

$$\int_{t_1}^{t_2} \frac{\partial M}{\partial t} dt = (M_2 - M_1)_\theta + \frac{1}{2}(V_2^2 - V_1^2)_\theta \tag{6}$$

$$D = \overline{V_\theta} \Delta t. \tag{7}$$

The left hand term in equation (6) represents the local change in the stream function. The local change is graphically determined by analysing the 12 hour local changes of ΔM at each upper-air station or data point. For the four time periods of this study, ΔM is analysed using an increment of 0.25×10^7 cm^2 sec^{-2}. ΔM is then averaged along the trajectory path to obtain an approximation to the left hand side of equation (6). Figure 6 illustrates the local change of M for the period 22 March 0000 GMT to 22 March 1200 GMT on the 330 K θ surface.

The second term on the right hand side of equation (6) expresses the change in kinetic energy of the horizontal wind. After converting the units of this kinetic energy term to the units of M (10^7 cm^2 sec^{-2}) and re-arranging terms, equation (6) can be written as

$$M_2 = M_1 + 0.0005 (V_1^2 - V_2^2)_\theta + \overline{\Delta M} \tag{8}$$

for V expressed in m sec^{-1}.

The units of equation (7), the distance equation, are converted to degrees latitude for a 6 hour trajectory, becoming

$$D \doteq 0.19\overline{V_\theta}\,. \tag{9}$$

The objective now is to locate a value of M at the final point on a trajectory path such that equations (8) and (9) are simultaneously satisfied. Detailed procedures for calculating isentropic air trajectories can be found in Danielsen's paper (1961). However, the procedures used for this study will be briefly outlined for one time period.

For the first 12 hour period, 22 0000 GMT to 22 1200 GMT, a representative sample of initial data points in and around the isotach center of the polar front jet and the subtropical jet streams is selected on the 22 0000 GMT M analysis for the four relevant θ surfaces. The first estimate of the path of the trajectory is obtained by sketching both the 22 0000 GMT and the 22 1200 GMT streamlines around one of the initial data points. An average streamline is determined by giving more weight to the 22 0000 GMT streamlines for the first 6 hour period and to the 22 1200 GMT for the second 6 hour period. A 6 hour trajectory is computed by equation (9) using the wind speed at the initial data point and is plotted along the average streamline using 1° increments. A mean wind at the 6 hour position is determined from the 22 0000 GMT and 22 1200 GMT isotach analyses. This mean wind is then averaged with the initial wind to determine an estimated mean wind over the first 6 hour period. Equation (9) is again employed to calculate a better estimate of the 6 hour trajectory position.

Using the mean wind at the 6 hour position, the trajectory for the

next 6 hour period is computed by equation (9). The winds at the 12 hour and 6 hour positions are averaged and this resulting mean wind is used to re-estimate the 12 hour position.

Now, the trajectory computed by using equation (9) must be tested by equation (8). To, calculate $\overline{\Delta M}$, the trajectory determined by the distance equation is superimposed on the respective ΔM analysis and divided into four equal segments. Simpson's rule is utilized to calculate the 12 hour local change of M integrated along the trajectory path. Having $\overline{\Delta M}$, V_1, V_2, and M_1, M_2 is computed.

At this stage in the procedure, an observed value of M_2, determined from the first estimate to the trajectory and the 22 1200 GMT M analysis, and a computed value of M_2, determined by equation (8), have been obtained. $M_{2\text{-obs}}$ is then compared to $M_{2\text{-comp}}$. If their absolute difference is equal to or less than 0.1×10^7 cm^2 sec^{-2}, the initial trajectory satisfies both equations and this trajectory represents the 12 hour air parcel movement on the isentropic surface.

Generally, for the first estimated trajectory, $\left| M_{2\text{-comp}} - M_{2\text{-obs}} \right|$ is greater than 0.1×10^7 cm^2 sec^{-2}. If this is the case, the 12 hour position calculated by equation (9) is moved perpendicular to the mean flow towards the $M_{2\text{-comp}}$ value obtained from equation (8). A new V_2 at this second estimated 12 hour position is determined from the 22 1200 GMT isotach analysis.

The initial trajectory is now adjusted throughout its entire path to conform to the second estimated 12 hour position. The resulting differences between the adjusted trajectory and the initial trajectory have changed the 6 hour position. Hence, a new mean wind over the first 6 hour period and the second 6 hour period is calculated by the method outlined previously.

Following the original procedures with the new 6 hour mean winds, a second estimated 12 hour trajectory position on the adjusted trajectory is computed. If $\left|M_{2\text{-comp}} - M_{2\text{-obs}}\right|_{\text{new}}$ is less than or equal to 0.1×10^{7} cm^2 sec^{-2}, the second estimated trajectory satisfies the distance and the energy equations simultaneously. If not, the previous procedures are again repeated until convergence is reached. Thus, an air parcel has been successfully tracked for 12 hours on an isentropic surface by successive approximations.

Figure 7 illustrates the final estimated trajectories for the 22 0000 GMT to 23 0000 GMT time period on the 330 K isentropic surface.

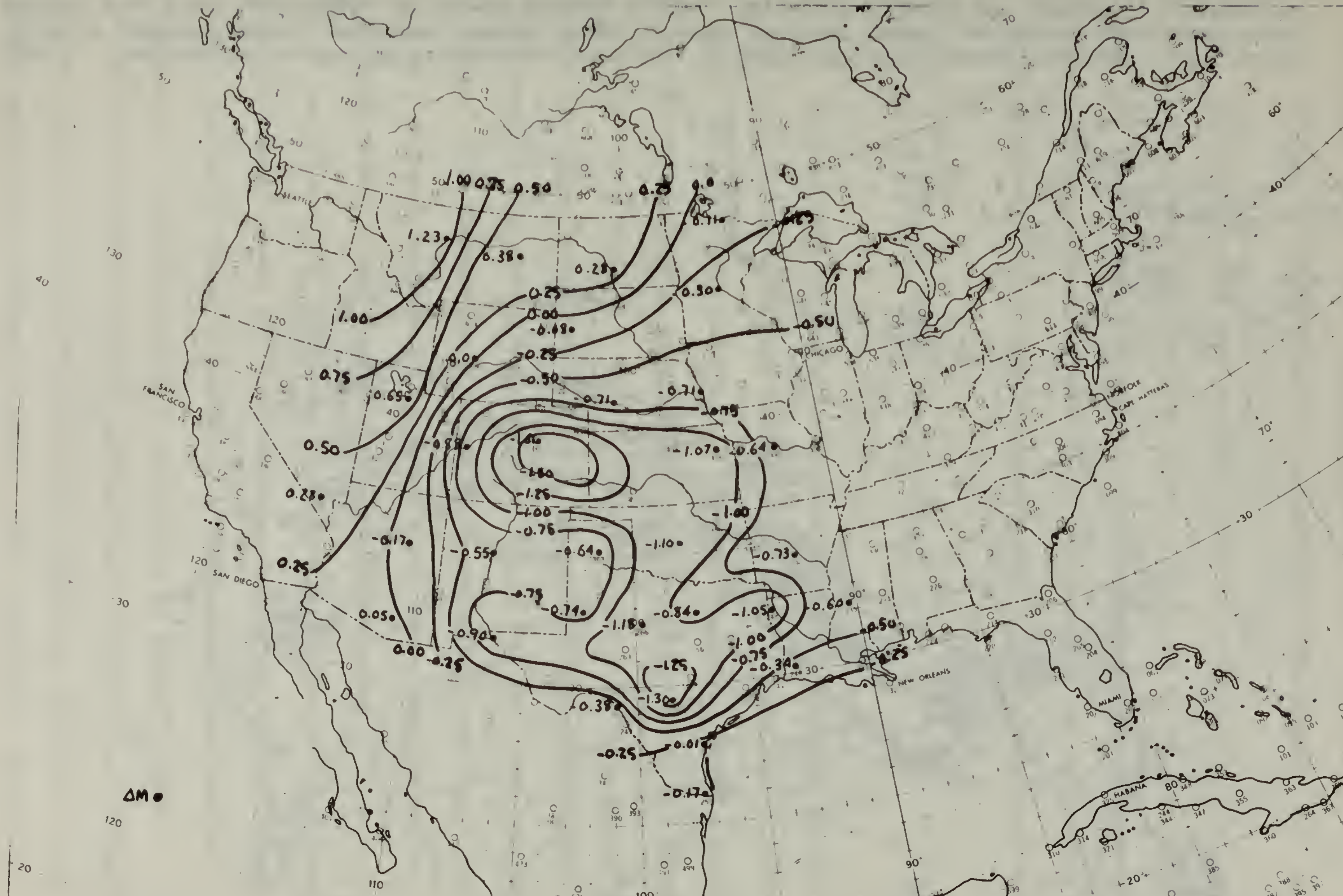


Fig. 6. 310K ΔM analysis for 22 March 1966, 0000 GMT to 1200 GMT. ΔM expressed in 10^7 cm^2 sec^{-2}.

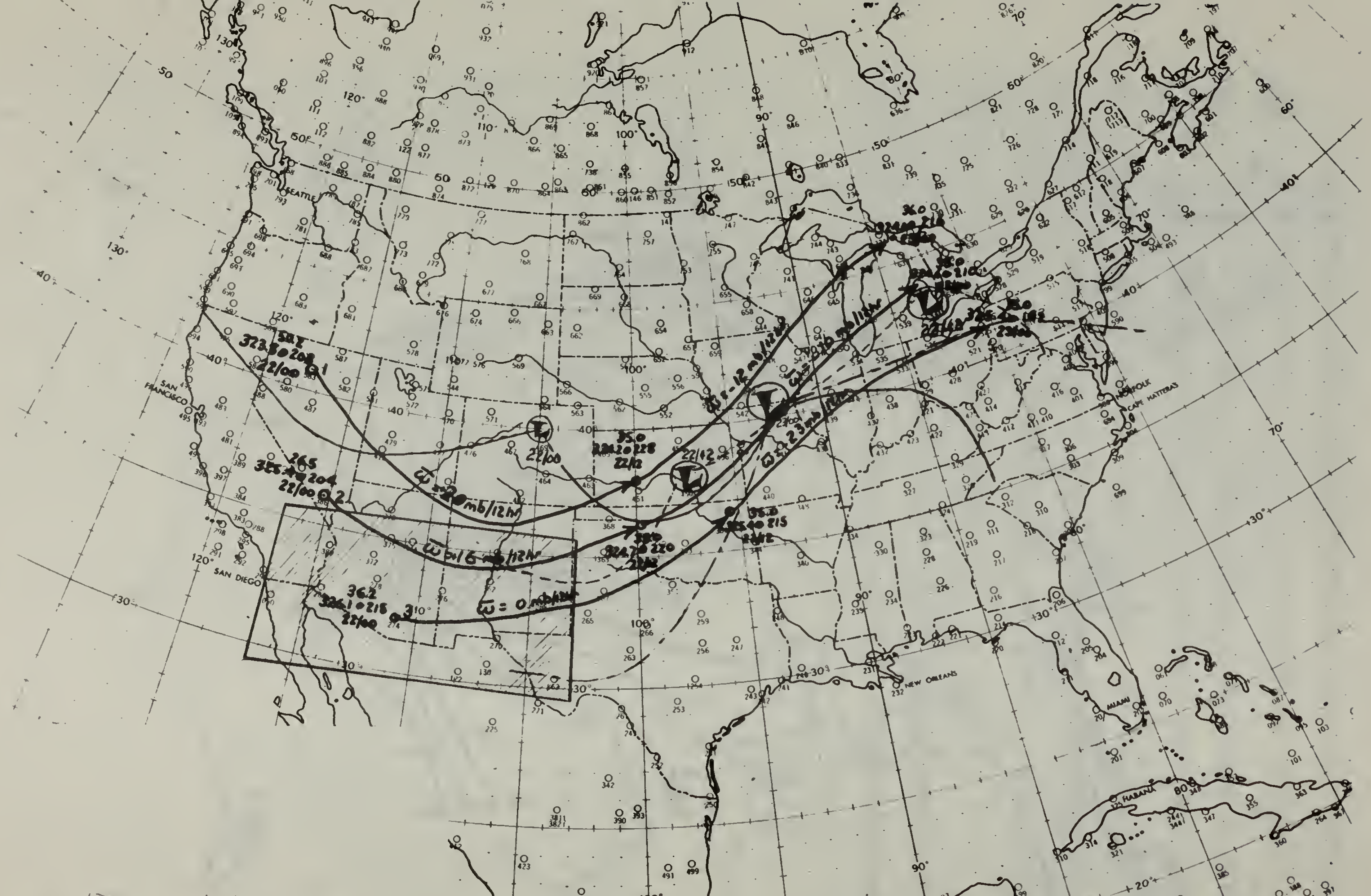


Fig. 7. Trajectories on the 330 K isentropic surface. 22 March 0000 GMT frontal positions, solid lines; 22 March 1200 GMT frontal positions, dotted lines; 23 March 0000 GMT frontal positions, dot-dashed lines. Hatched area shows approximate jet stream merging region. Values of M (units 10^7 cm^2sec^{-2}), of pressure (mb), of wind speed (m sec^{-1}), are entered numerically for the initial, 12 hour, and 24 hour trajectory positions. $\overline{\omega}$ (mb/12hrs) is entered above each trajectory. Note that Trajectory 3 indicates apparent cross-over from the subtropical jet stream flow to the polar front jet stream flow.

SECTION VI

RESULTS OF THE ISENTROPIC AIR TRAJECTORY COMPUTATIONS

After computing a representative sample of trajectories for each of the four isentropic surfaces, (310 K, 320 K, 330 K, and 335 K), for all four time periods, the trajectories are superimposed on the respective pressure analyses, so that P_θ can be determined for the initial and final position. $\bar{\omega}$ is then calculated for each 12 hour trajectory, where

$$\bar{\omega} = \frac{1}{\Delta t} \int_{t_1}^{t_2} \frac{dP_\theta}{dt}\, dt = (P_{\theta_2} - P_{\theta_1})\ \mathrm{mb/12\,hrs}. \tag{10}$$

To illustrate the three-dimensional air parcel movement, an analysis of trajectory position relative to the surface front position is made. The positional relationship between a trajectory and the moving surface frontal system, as shown in Figure 7, appears quite consistent for all four θ surfaces. Trajectory 2 on the 330 K surface, initially over Las Vegas, Nevada (Station 386), has an average downward vertical motion ($\bar{\omega}$ positive) of +16 mb/12hrs for the 22 0000 GMT to 22 1200 GMT period. This downward vertical motion is reasonable since the Trajectory 2 position is generally lagging the cold front position for the 12 hour period — thus remaining in a subsidence region.

As Trajectory 2 progresses to the northeast, its position relative to the frontal system is, on the average, leading the surface system. This leading situation is indicative of the average upward vertical motion of -1 mb/12hrs for the 22 1200 GMT to 23 0000 GMT period.

This leading and lagging relative relationship between isentropic air trajectories and the surface frontal system was consistent for all time periods and isentropic surfaces. Thus, through the laborious 4

level computations, a physical understanding of air trajectory three-dimensional motion has been attained. In addition, a mental picture of this motion can be generated by relating these trajectories to the surface phenomenon.

SECTION VII

TESTING THE HYPOTHESIS

Recent studies by Danielsen (1961), Reiter and Whitney (1965), and Mahlman (1965) have investigated cases of apparent jet stream cross-over at isentropic levels below 310 K. Assuming the cross-over phenomenon does exist at the lower levels of the atmosphere, it is reasonable to inquire as to the existence of a compensatory cross-over flow above the 310 K isentropic level. Therefore, this hypothesis will be tested by further analyses of trajectories associated with the respective jet streams within the merging region.

The isentropic air trajectories are analysed for their positions relative to isotach centers of the polar front jet and the subtropical jet streams. The trajectories are further analysed for their positions relative to the region of apparent jet stream merging. As illustrated in Figure 8, Trajectory 1 at 22 0000 GMT is located within the 50 m sec^{-1} isotach center of the polar front jet stream on the 335 K surface. Maintaining a cyclonic curvature with an average downward vertical motion of +8 mb/12hrs for the succeeding 12 hour period, an air parcel associated with Trajectory 1 remains in the polar jet flow and by 22 1200 GMT is well out of the merging region. Referring again to Figure 8, an air parcel associated with Trajectory 2 follows a similar path as that of Trajectory 1, but is displaced more to the south throughout the 22 0000 GMT to 22 1200 GMT period. As before, this trajectory can be tracked through the merging region and on to the northeast.

After analysing the trajectories associated with the polar front jet stream on the four θ surfaces for the four time periods, the mean three-dimensional flow of air parcels in the polar front jet is deter-

mined to be basically cyclonic in nature — descending when moving southeast and ascending when moving northeast. This mean flow corroborates previous studies.

For the 22 0000 GMT to 22 1200 GMT period, the apparent jet merging region is over New Mexico and Arizona. Trajectory 3 of Figure 8 at 22 0000 GMT begins within the merging region over Tucson, Arizona (Station 274). An air parcel following this trajectory appears to disassociate from the main flow of the subtropical jet and proceeds to the northeast with an average upward vertical motion of -10 mb/12hrs for the first 12 hour period. By 22 1200 GMT, the air parcel associated with Trajectory 3 has entered the isotach center over Missouri and continues to move northeastward toward the Great Lakes region. This phenomenon of apparent disassociation of air parcels from the subtropical stream flow is evident on the four θ surfaces for the trajectories with initial position over Tuscon at 22 0000 GMT.

Trajectory 4 of Figure 8 is located over El Paso, Texas (Station 270) at 22 0000 GMT. Unlike Trajectory 3, an air parcel associated with Trajectory 4 remains within the anticyclonically curving subtropical jet stream flow for the succeeding 24 hour time period.

To substantiate the statement made in the previous paragraph concerning apparent disassociation of air parcels from the subtropical jet stream flow on a θ surface other than 335 K, refer again to Figure 6. Trajectory 3 on the 330 K surface also begins over Tucson, Arizona at 22 0000 GMT. This trajectory path appears to cross-over and by 22 1200 GMT possesses the characteristic flow pattern of the polar front jet stream.

By 23 March 0000 GMT, the jet stream merging region is located over Texas. Trajectory 2 on the 330 K isentropic surface in Figure 9,

initially located over Del Rio, Texas (Station 261), appears to continue within the subtropical jet influence and maintains an average upward vertical motion of -29 mb/12hrs for the 23 0000 GMT to 23 1200 GMT time period.

The isotach analyses of the four isentropic surfaces for the 23 1200 GMT to 24 0000 GMT period defines the merging region of the polar front and the subtropical jet streams most clearly. Trajectory 3 of Figure 10 was selected because not only was the air parcel following this trajectory path associated with the subtropical jet flow, but the 23 1200 GMT position over Midland, Texas (Station 265) was well within the merging region. Trajectory 3 on the 320 K and 330 K isentropic surfaces appears to cross-over and proceed cyclonically to the northeast, apparently identifying itself with the polar front jet flow at these levels as illustrated in Figure 10. However, trajectories on the 335 K and 310 K surfaces located over Midland at 23 1200 GMT are displaced to the south of the 320 K and 330 K trajectory position, indicating a continued association with the subtropical jet stream flow. It is interesting to note that Trajectory 4, located initially on the anticyclonic side of the subtropical jet stream, apparently remains well within this flow.

The subtropical jet is located north of its normal position for the 23 March 1200 GMT to 24 March 0000 GMT period. Trajectory 3 of Figure 10 is initially located on the cyclonic side of the jet and in the central section of the merging region. Trajectories computed to the south, or on the anticyclonic side of the subtropical jet stream, follow the classical anticyclonic path over the southern United States as shown in Figures 7 and 9.

Potential vorticity (P) of an air parcel is known to be a conservative property for adiabatic and frictionless air motions. As a further test for the four trajectories with apparent cross-over flow, P is computed for the initial, 12 hour, and 24 hour isentropic trajectory positions. If the three P values do not vary appreciably, this lends further credence to the validity of the trajectories indicating cross-over flow. Consequently, the fact that potential vorticity is conserved, as shown in Table 2, helps substantiate the results of the isentropic trajectory computations.

As shown in Figure 8, Trajectory 3 on the 335 K isentropic surface for the first 12 hours follows a cyclonic path and for the second 12 hours an anticyclonic path. If the assumption of conservation of potential vorticity is valid for this assumed frictionless and adiabatic motion, then the large 24 hour relative vorticity change which reflects this curvature change must be explained by a significant increase of one of the parameters in the P equation. One possibility is a rapid increase in the Coriolis parameter, but for this trajectory, variations in f are small as shown in Table 2. However, Table 2 shows that the relative vorticity decrease is compensated by a rapid static stability increase. To some extent this argument helps justify the physical mechanisms involved in the cross-over phenomenon.

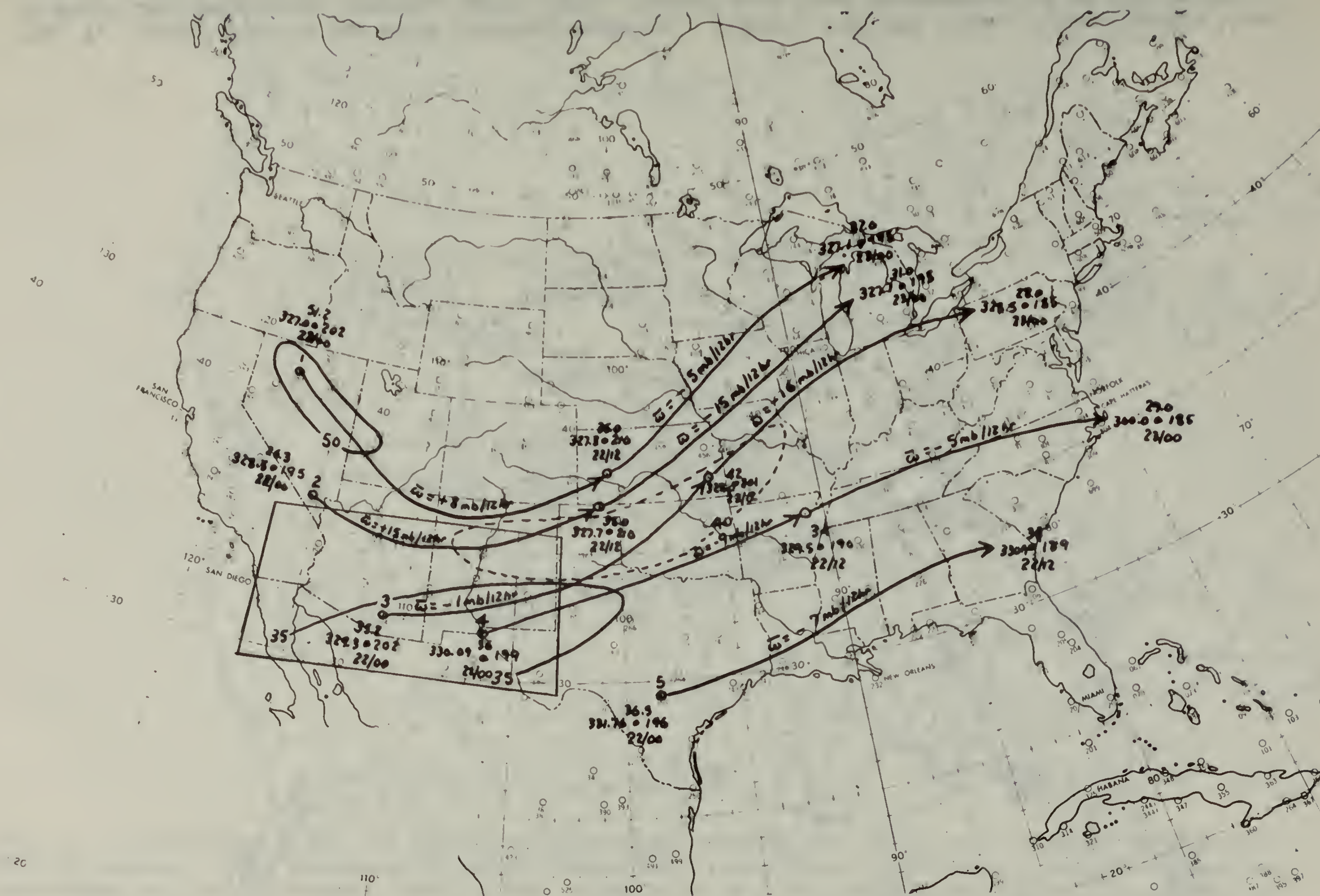


Fig. 8. Trajectories on the 335 K isentropic surface. 22 March 0000 GMT isotach centers, solid lines; 22 March 1200 GMT isotach centers; dashed lines. Hatched area shows approximate jet merging region. Refer to Fig. 6 for units of M, P_{θ}, and dd. ϖ (mb/12hrs) entered above each trajectory.

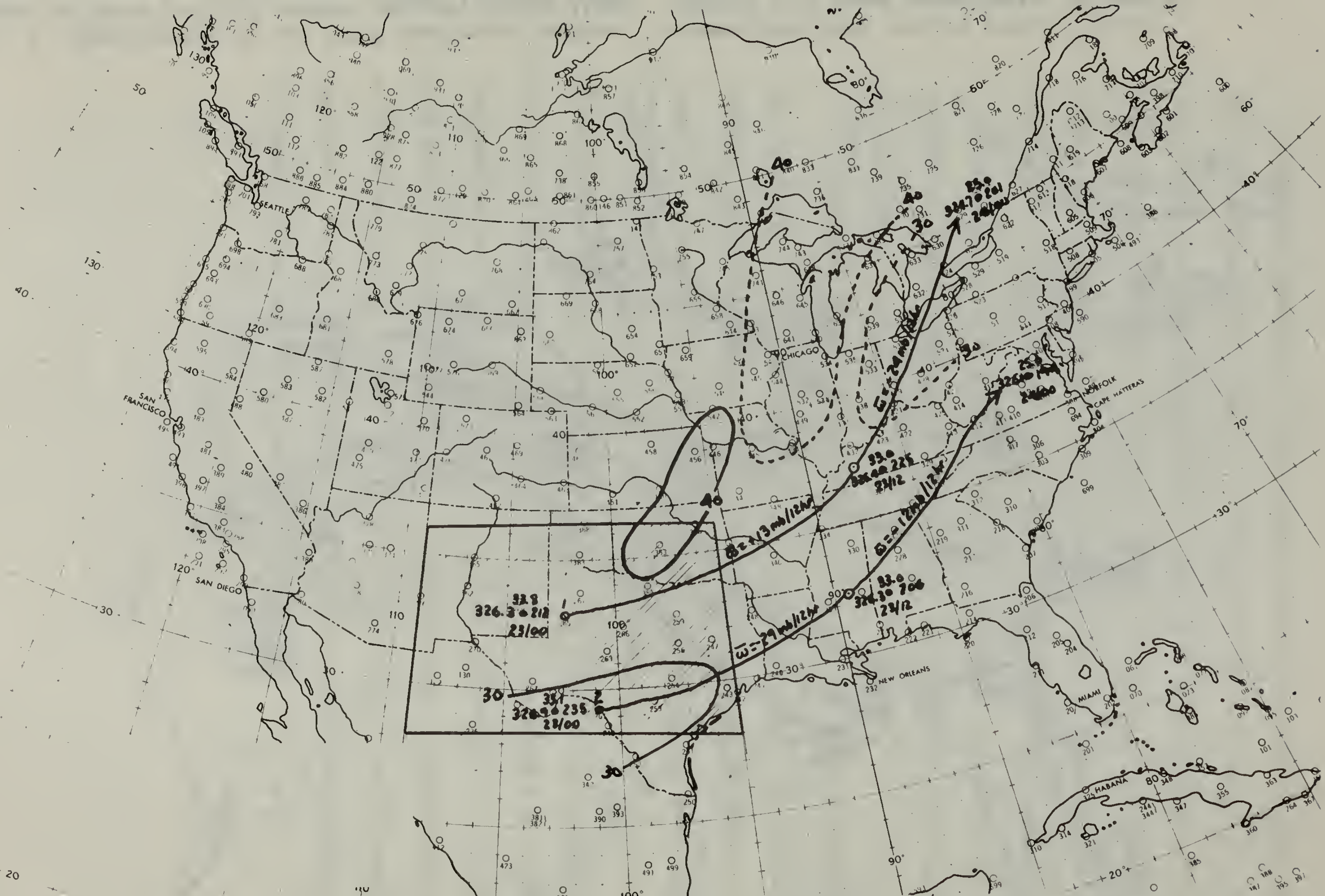


Fig. 9. Trajectories on the 330 K isentropic surface. 23 March 0000 GMT isotach centers, solid lines; 23 March 1200 GMT isotach centers, dashed lines. Hatched area shows approximate jet merging region. Refer to Fig. 6 for units of M, P_θ, and dd. $\overline{\omega}$ (mb/12hrs) entered above each trajectory. Note that Trajectory 3 indicates apparent cross-over from the subtropical jet stream flow to the polar front jet stream flow.

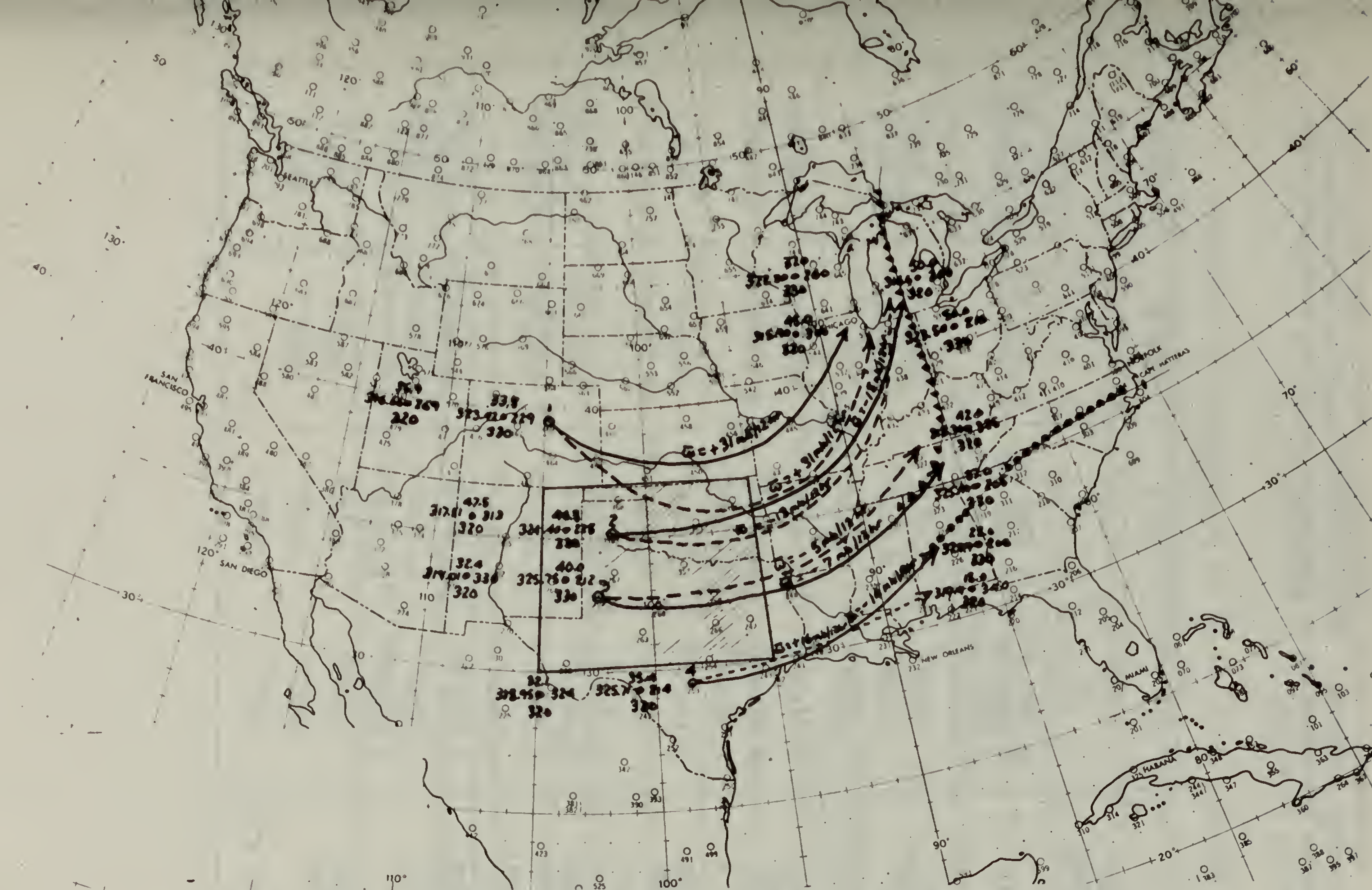


Fig. 10. Trajectories on the 320 K and 330 K isentropic surfaces for the 23 March 1200 GMT to 24 March 0000 GMT period. 320 K trajectories, dashed lines; 330 K trajectories, solid lines. Hatched area shows approximate jet merging region. Refer to Fig. 6 for units of M, P_θ, which along with θ ($^{\circ}$K), are entered numerically for the initial and 12 hour trajectory positions. $\overline{\omega}$ (mb/12hrs) entered above each trajectory. The line of triangles is the 24 March 0000 GMT estimated polar front jet position; the line of circles is the estimated subtropical jet stream 24 March 0000 GMT position. Note that Trajectory 3 indicates apparent cross-over from the subtropical jet stream flow to the polar front jet flow.

Table 2. Approximate values of potential vorticity computed at relavant trajectory positions. Note the static stability and absolute vorticity values corresponding to respective trajectory curvatures shown in Figures 7, 8, and 10.

	θ SURFACE			
	330 K	335 K	320 K	330 K
FIGURE TRAJECTORY	7 3	8 3	10 3	10 3
DATE	22 0000 GMT 22 1200 GMT 23 0000 GMT	22 0000 GMT 22 1200 GMT 23 0000 GMT	23 1200 GMT 24 0000 GMT	23 1200 GMT 24 0000 GMT
STATIC STABILITY (deg cm $sec^{+2}g^{-1}$)	$3.8x10^{-5}$ $4.5x10^{-5}$ $8.0x10^{-5}$	$3.8x10^{-5}$ $5.4x10^{-5}$ $8.0x10^{-5}$	$0.53x10^{-5}$ $0.50x10^{-5}$	$5.6x10^{-5}$ $5.3x10^{-5}$
CORIOLIS PARAMETER (sec^{-1})	$0.73x10^{-4}$ $0.83x10^{-4}$ $0.93x10^{-4}$	$0.73x10^{-4}$ $0.83x10^{-4}$ $0.93x10^{-4}$	$0.79x10^{-4}$ $0.87x10^{-4}$	$0.79x10^{-4}$ $0.83x10^{-4}$
SHEARING VORTICITY (sec^{-1})	$0.30x10^{-4}$ 0.0 0.0	$0.30x10^{-4}$ $0.12x10^{-4}$ $-0.06x10^{-4}$	$-0.20x10^{-4}$ $-0.25x10^{-4}$	0.0 $-0.06x10^{-4}$
CURVATURE VORTICITY (sec^{-1})	$0.28x10^{-4}$ $0.27x10^{-4}$ $-0.28x10^{-4}$	$0.27x10^{-4}$ $0.31x10^{-4}$ $-0.22x10^{-4}$	$0.27x10^{-4}$ $0.34x10^{-4}$	$0.32x10^{-4}$ $0.30x10^{-4}$
ABSOLUTE VORTICITY (sec^{-1})	$1.31x10^{-4}$ $1.10x10^{-4}$ $0.65x10^{-4}$	$1.30x10^{-4}$ $1.10x10^{-4}$ $0.65x10^{-4}$	$0.86x10^{-4}$ $0.96x10^{-4}$	$1.11x10^{-4}$ $1.19x10^{-4}$
POTENTIAL VORTICITY (deg cm sec g^{-1})	$5x10^{-9}$ $5x10^{-9}$ $5x10^{-9}$	$5x10^{-9}$ $6x10^{-9}$ $5x10^{-9}$	$5x10^{-9}$ $5x10^{-9}$	$6x10^{-9}$ $6x10^{-9}$

SECTION VIII

CONCLUSIONS

As indicated in Figures 7, 8, and 10 and their subsequent analyses, cross-over of air parcels in the subtropical jet stream flow to the polar front jet flow apparently exists between the 310 K and 335 K isentropic surfaces. This conclusion is dependent upon the validity of the adiabatic assumption. However, referring again to Figures 7, 8 and 10, it can be observed that small directional wind shears in the vertical exist through the 10° isentropic layer. Therefore, diabatic effects, even if present, would not appreciably affect the results. An additional implication from these analyses is the existence of a mass transport phenomenon in the jet stream region as observed by Reiter and Whitney (1965).

The cross-over phenomenon of air parcels initially in the polar front jet stream is not observed in this case study for the relevant isentropic surfaces. However, the apparent lack of air parcel cross-over to the subtropical jet stream flow at these θ levels might be explained by the limited number of isentropic surfaces, synoptic situations, and parameters utilized in this research.

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APPENDIX I

The Montgomery stream function computer program developed for this study (Sections A and B).

APPENDIX I: Section A. List of symbols used in the computer program.

SYMBOL	MEANING
DD1	wind direction at first standard level below TH1
DD2	wind direction at first standard level above TH1
DDTH	interpolated wind direction at TH1
F	Montgomery stream function
F1	first segment of F
F2	second segment of F
F3	third segment of F
FF1	wind speed at first standard level below TH1
FF2	wind speed at first standard level above TH1
FFTH	interpolated wind speed at TH1
PP	pressure at first standard level below TH1
PP2	pressure at first standard level above TH1
PPB	pressure at first level below TH1
PPT	pressure at first level above TH1
PTH	pressure at TH1
STAB	stability parameter $= -\frac{\partial \theta}{\partial P}$
T	temperature
TB	T at first level below TH1
TBAR	average T of layer between PP and PP2
TH	potential temperature
THB	TH at first level below TH1
TH1	assigned TH value
THT	TH at first level above TH1
TT	T at first level above TH1

SYMBOL	MEANING
TTH	T at TH1
ZTH	geopotential height of TH1

APPENDIX I: Section B. The Montgomery stream function computer program.

```
C
C     MONTGOMERY STREAM FUNCTION COMPUTER PROGRAM -- 1 JUNE 1968
C
C     RADIOSONDE DATA FOR  22 MARCH 0000 GMT TO 24 MARCH 0000 GMT
C     1966.  FIVE OBSERVATION TIMES -- RESPECTIVE MATRIX A,B,C,D,E.
C
      DIMENSION A(1190,5), B(1478,5), D(1290,5), E(1484,5), C(1270,5),
     1 G(1484,5), TH(1484), T(1484)
      READ (5,500) ((A(I,J), J = 1,5), I = 1, 1190)
      READ (5,500) ((B(I,J), J = 1, 5), I = 1, 1478)
      READ (5,500) ((C(I,J), J = 1,5), I = 1, 1270)
      READ (5,500) ((D(I,J), J = 1,5), I = 1, 1290)
      READ (5,500) ((E(I,J), J = 1,5), I = 1,1484)
  500 FORMAT (10F8.0)
      WRITE (6,600)
  600 FORMAT (1H1)
      N = 1
    1 IF (N .EQ. 1) GO TO 2
      IF (N .EQ. 2) GO TO 3
      IF (N .EQ. 3) GO TO 4
      IF (N .EQ. 4) GO TO 5
      IF (N .EQ. 5) GO TO 6
      IF (N .EQ. 6) GO TO 17
    2 M = 1190
      GO TO 7
    3 M = 1478
      GO TO 7
    4 M =  1270
      GO TO 7
    5 M = 1290
      GO TO 7
    6 M = 1484
    7 DO 10 I = 1, M
      DO 10 J = 1, 5
      IF (N .EQ. 1) GO TO 20
      IF (N .EQ. 2) GO TO 21
      IF (N .EQ. 3) GO TO 22
      IF (N .EQ. 4) GO TO 23
      IF (N .EQ. 5) GO TO 24
   20 G(I,J) = A(I,J)
      GO TO 10
   21 G(I,J) = B(I,J)
      GO TO 10
   22 G(I,J) = C(I,J)
      GO TO 10
```

```
   23 G(I,J) = D(I,J)
      GO TO 10
   24 G(I,J) = E(I,J)
   10 CONTINUE
   25 DO 11 I = 1, M
   11 WRITE (6,610) I, (G(I,J), J = 1, 5)
  610 FORMAT (20X, I10, 5X, 5F10.1)
C
C     CONVERT TEMPERATURES AND COMPUTE POTENTIAL TEMPERATURES
C
      WRITE (6,612)
  612 FORMAT (1H1)
      DO 12 I = 1, M
      IF (G(I,3) .EQ. 777.0) GO TO 8
      T(I) = G(I,2) + 273.2
      TH(I) = T(I) * ((1000.0 / G(I,1)) ** 0.2857)
      GO TO 18
    8 T(I) = 777.0
      TH(I) = 777.0
   18 WRITE (6,611) I, T(I), TH(I)
  611 FORMAT (5X, I10, 2F10.1)
   12 CONTINUE
C
C     CHECK FOR DISCREPENCIES IN POTENTIAL TEMPERATURES ABOVE 800 MB
C
      WRITE (6,620)
  620 FORMAT (1H1, T10, 'DISCREPENCIES IN THETA VALUES', ///)
      DO 13 I = 1, M
      IF (TH(I) .EQ. 777.0) GO TO 13
      IF (G(I,1) - 800.0) 40, 40, 13
   40 IF(TH(I+1) - TH(I)) 41, 13, 13
   41 WRITE (6,630) I, TH(I), TH(I+1)
  630 FORMAT (5X, I10, 2F10.1, /// )
   13 CONTINUE
C
C     ASSIGN POTENTIAL TEMPERATURES FOR COMPUTATION
C
      TH1 = 290.0
      GO TO 50
   14 TH1 = TH1 + 5.0
      IF (TH1 .GT. 350.0) GO TO 16
   50 WRITE (6, 640)
  640 FORMAT (1H1)
      FFTH = 0.0
      DDTH = 0.0
```

```
C     SEARCH DATA FOR VALUES ABOVE AND BELOW LEVEL BEING COMPUTED
C
      DO 15 I = 1, M
      IF (TH(I) .EQ. 777.0) GO TO 15
      IF (TH(I) - TH1) 51, 52, 53
   51 GO TO 15
   52 TTH = T(I)
      GO TO 54
   53 THT = TH(I)
      TT = T(I)
      PPT = G(I,1)
      IF (TH(I-1) .EQ. 777.0) GO TO 15
      IF (TH(I-1) - TH1) 55, 15, 15
   55 TB = T(I-1)
      PPB = G(I-1,1)
      THB = TH(I-1)
C
C     COMPUTE PRESSURE AND TEMPERATURE AT LEVEL OF INTEREST
C
      TTH = TB + (TT - TB) * ((TH1 - THB) / (THT - THB))
   54 PTH = 1000.0 * ((TTH / TH1) ** 3.5001)
C
C     FIND NEAREST STANDARD LEVEL
C
      IPP = PTH / 50.0
      AAA = IPP * 50
      L = I
   60 IF (G(L,1) .EQ. AAA) GO TO 61
      L = L + 1
      GO TO 60
   61 PP = G(L,1) + 50.0
      J = L
   62 IF (G(J,1) .EQ. PP) GO TO 63
      J = J - 1
      GO TO 62
   63 PP = G(J,1)
      HGT = G(J,3)
      FF1 = G(J,5)
      DD1 = G(J,4)
      AA = 0.0
   70 IF (PTH - G(J+1,1)) 71, 72, 72
   71 AA = AA + (T(J) + T(J+1)) * (G(J,1) - G(J+1,1))
      J = J + 1
      GO TO 70
```

```
   72 AA = AA + (T(J) + TTH) * (G(J,1) - PTH)
   74 TBAR = (1.0 / (2.0 * (PP - PTH))) * AA
      PP2 = PP - 50.0
   64 IF (G(J,1) .EQ. PP2) GO TO 65
      J = J + 1
      GO TO 64
   65 PP2 = G(J,1)
      FF2 = G(J,5)
      DD2 = G(J,4)
C
C     COMPUTE MONTGOMERY STREAM FUNCTION IN THREE SEGMENTS
C
      Z = 1.E6
      F1 = 10.046 * TTH * Z
      F2 = 9.8 * HGT * 1.E4
      F3 = 2.8704 * Z * TBAR * (ALOG(PP) - ALOG(PTH))
C
C     INTERPOLATE WIND DIRECTION AND WIND SPEED
C
      IF (FF1 .LT. 888.0) GO TO 80
      FFTH = 888.0
      DDTH = 888.0
   80 IF (FF2 .LT. 888.0) GO TO 81
      FFTH = 888.0
      DDTH = 888.0
      GO TO 88
   81 FFTH = FF1 + (FF2 - FF1) * ((PP - PTH) / 50.0)
      DD3 = DD2 - DD1
      IF (DD3 - 180.0) 82, 83, 83
   83 DD3 = DD3 - 360.0
      GO TO 85
   82 IF (DD3+ 180.0) 84, 85, 85
   84 DD3 = DD3 + 360.0
   85 DDTH = DD1 + DD3 * ((PP - PTH) / 50.0)
      IF (DDTH) 86, 88, 87
   86 DDTH = DDTH + 360.0
      GO TO 88
   87 IF (DDTH - 360.0) 88, 89, 89
   89 DDTH = DDTH - 360.0
   88 CONTINUE
C
C     COMPUTE STABILITY FACTOR
C
      STAB = (THT - THB) / (PPB - PPT)
C
```

```
C      COMPUTE MONTGOMERY STREAM FUNCTION
C
       F = F1 + F2 + F3
C
C      COMPUTE HEIGHT OF THETA SURFACE
C
       ZTH = HGT - (2.8704 * TBAR / 9.8) * (ALOG(PTH) - ALOG(PP))
C
       WRITE (6,650) I, STAB, F1, F2, F3, F
  650  FORMAT (5X, I10, 5X, F6.3, 5X, 3P4E15.5)
       WRITE (6,660) TH1, PTH, TTH, ZTH, DDTH, FFTH
  660  FORMAT (5X, 6F10.1, ///)
   15  CONTINUE
       GO TO 14
   16  N = N + 1
       GO TO  1
   17  STOP
       END
```

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13. ABSTRACT

A developing surface frontal system with an overlying polar front jet and subtropical jet stream merging region was present over the continental United States during 22 to 24 March, 1966. Possible cross-over flow between these two jet streams has been studied in detail by isentropic air trajectories at four potential temperature levels from 310 K to 335 K.

The results of the trajectory analyses on the four θ surfaces have indicated a cross-over of air parcels from the subtropical jet stream to the polar front jet stream. No evidence has been found for a reciprocal relationship for air parcels initially associated with the polar front jet between 310 K and 335 K isentropic levels.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Isentropic Trajectory						
Montgomery Stream Function						
Potential Vorticity						
Jet Stream Cross-over						